X.—*On certain Improvements in the Construction of Galvanometers: on Galvanometers in general: and on a new Instrument for measuring the relative Force of Magnetism in compound Needles intended to be nearly Astatic.* By MICHAEL DONOVAN, Esq.

Read May 22, 1848.

THE galvanometer, in the present day, has become a most important instrument of research, whether it be considered as a measure of electricity or of heat. In the latter capacity, it exceeds all others in sensibility and the promptness of its indications; and when it is recollected that by its aid facts have been ascertained which had been erroneously represented by the thermometer, that degrees of heat have been estimated to which the thermometer was in some cases almost insensible, and in others inapplicable, its value and capabilities need no encomium. But it is necessary that, for delicate purposes, we should have the instrument in its utmost attainable state of perfection. Under such impressions, I have made some efforts to improve it; and believe I have succeeded in rendering it more certain and accurate in its results, as well as more sensible in its indications.

The sensibility of a galvanometer is increased when its construction is such, that the two layers of the wire coil, between which the compound or double needle lies, are as near as possible to each other, the consequence being that the lower bar of the compound needle will be very close to both. The upper bar should be equally near the upper layer of the coil. The proximity of the bars to the coil is one of the great sources of sensibility; but, to permit this, many things must be attended to.

In the first place, however carefully the wire of the coil may have been covered with silk or cotton, there will always be a number of fibres projecting

from the material. They are short it is true; but when the bars of the needle are very close to the three acting faces of the coil, these fibres are sometimes sufficiently long, resisting, and numerous, to obstruct the motions of the compound needle when in a state of great sensibility. The following plan succeeded in removing this source of uncertainty.

The wire, well covered with silk, is wound on a brass frame, each round so tight and close to the adjoining one, that the first layer may lie perfectly flat, without springing or bellying in any part. When the first layer has been wound from the beginning to the end of the frame, it is to be wound back again; and if the rounds of the first layer have been put on very compactly against each other, they will support the second layer without allowing the wire to force itself between any two which lie underneath. The flatness of the first layer will insure the same perfection for the second; and equal attention to tightness and flatness in winding the third layer, or fourth, if there be one, will produce a coil of great regularity and closeness, and of equal thickness,—qualities of the greatest utility.

Under these circumstances, it is obvious that the frame must be strong enough to sustain the collective tension of such a number of coils; and therefore brass, well covered in the touching parts with hard varnish, is to be preferred to ivory; although the latter is often used on account of its being a non-conductor. The four sides, which constitute the parallelogram on which the coil is wound, would not, without being inconveniently clumsy, afford sufficient resistance to this tension, but that the two end pieces of the frame, instead of being mere bars like the side pieces, constitute portions of a circle at the inner side, and are flat at the outer.

From what has been described, it is evident that the vacancy between the layers of the coil being but one-eighth of an inch, the numerous filaments projecting from the silk or cotton must be even more likely than in ordinary cases to obstruct the needle: and the very means adopted for securing sensibility would also react against that result, but for the following construction. Two plates of very thin, well-hammered brass are soldered to the two arches in such a manner as to connect them, and constitute what may be called a floor and a ceiling to the narrow chamber in which the lower bar of the compound needle rotates, thus effectually removing all possibility of obstruction by filaments, and

greatly adding to the strength of the frame. The coil is wound round the outside of the frame and its brass plates, leaving the internal circular chamber of brass for the uninterrupted oscillations of the enclosed needle. Its vertical width is reduced by the two brass plates to one-eighth of an inch.

But the upper bar of the needle would still be liable to obstructions from filaments of the upper layer of coil, were it not that a circular plate of well-hammered silvered brass lies loosely on it, and exactly fills up the interior of the circle on which the graduation is engraved.

In order to permit the compound needle to be placed within, and removed from its berth in the chamber, as occasion may require, there is a slit along the middle of what I have (for want of a better name) called its ceiling, so narrow as barely to admit the lower bar of the needle. To keep the wire of the coil and its filaments in situation, without encroaching on this slit, its edges are guarded all round by an elevated margin* of very thin sheet brass, which stands exactly as high as the thickness of the coil. The circular silvered brass plate above mentioned, although described as one piece, really consists of two semicircles, the diametrical junction of which is so accurately fitted, that it appears as a straight engraved line upon one circular plate: it represents the magnetic meridian of the galvanometer. When the needle is to be removed, the semicircles are easily pushed up from below. Between the semicircles, and in their common centre, there is a small hole, which permits the spindle or connecting axis of the two bars of the compound needle to play freely. In the top of this spindle is a very small hole, barely large enough to receive the silk fibre which sustains the compound needle. Thus the two bars, which constitute the compound needle, are brought as near as possible to the three faces of the coil, without risk of obstruction. The chamber in which one bar of the needle rotates may be as vertically narrow as will allow free motion; one-eighth of an inch will be sufficient. In so narrow a space, it is obvious that any deviation from the horizontal position of the coil and frame would cause obstruction to the movements of the needle: the same would happen also if the needle were not accurately balanced on its spindle, and therefore on the suspending fibre of silk. The

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* The coil must be wound as closely as possible against this margin on both sides; for here the energy of a voltaic current is most required to overcome the inertia of the needle.

horizontal portion is attainable by means of a detached spirit level and levelling screws; and the balance of the needle is regulated by a very small slider made of brass foil. It will be often found necessary to have a slider even on each member of the compound needle; for as the intensity of its magnetism is sometimes stronger, sometimes weaker, in consequence of spontaneous or induced changes, the dip will affect it more or less'; and hence the necessity of the sliding equipoise to maintain the horizontal position in so narrow a chamber. The second slider becomes necessary when the poles are reversed in the manner hereafter described.

The level and levelling screws afford the means not only of rendering the plane of the chamber perfectly horizontal, but of giving true verticity to the pillar from the cross-bar of which the needle hangs. Without such a precaution the spindle of the needle would not freely rotate in the small hole made for it in the meridian line of the circular plate, or rather between the two semicircular plates.

To give greater precision to the centrality of this spindle, the hole in its top is made exceedingly small, and through it is looped the suspending silk fibre, the other end of which is looped through an equally small hole in a pin which may be secured by a thumb-screw, in the cleft end of a horizontal cross-bar, moveable in every direction at the top of the pillar. The use of having the holes so small is to secure the silk from shifting, and thus altering the balance or position of the needle. The length of silk fibre which I conceive to be sufficient is $7\frac{1}{2}$ inches, exclusive of what is looped above and below.

When occasion requires the compound needle to be removed from the galvanometer, the thumb-screw which screws against the pin in the cleft of the cross-bar at the top of the pillar is to be loosed; the pin with the silk fibre is to be drawn out; the two semicircular plates which lie within the graduated circle are to be pushed up from below, and the needle withdrawn. This facility of removing and replacing the needle is a great advantage when its magnetism requires regulation; and beside this the silk fibre often becomes twisted by the rapid spinning of the needle which certain experiments occasion and even require: it is prevented from untwisting by the polarity of the needle; but if the needle be held between the fingers while the pin hangs down by its fibre of silk, the latter will untwist itself; and when the pin ceases to spin, the whole

may be replaced. Torsion, even of so slender a fibre, has more effect in impairing sensibility than might be supposed.

The frame of the coil is screwed on a strong circular plate of brass, surrounded by a hoop sufficient to secure the French shade which covers the whole. The solid vertical axis of this plate turns smoothly and slowly in a ground socket, by means of a crown wheel fixed to the plate, acted on by a pinion and thumb-screw attached to the tripod on which the whole instrument stands. The levelling screws pass through the tripod, and rest in so many holes in a circle of brass screwed to a mahogany stand, in the bottom of which should be a drawer to contain various necessaries. On the stand fits a mahogany cover or box, with fastenings. The ends of the coil pass down through two holes in the circular brass plate, bushed with ivory, and are soldered underneath the plate, each to an insulated binding screw, situated one on each side of the meridian line. Between the binding screws, and affixed to the circular brass plate, is a horizontal, hollow, square trunk, three inches in length: each side of the interior measures about three-sixteenths of an inch: it is fixed in the direction of the magnetic meridian line of the galvanometer, and has a continuation of this line engraved on its upper surface. At the end of the trunk, and on the meridian line, is erected a short, sharp brass point, on which may be occasionally placed a common compass needle. When the galvanometer is to be used, the compass needle is to be placed on the brass point, and the thumb-screw underneath turned until the point of the compass needle and the meridian line coincide precisely. The instrument is now set; the compass needle is to be removed, lest it interfere with the astatic needle: the latter should also have been previously removed, as it would equally interfere with the compass needle. The necessity of thus setting the instrument by a detached compass needle, and of not depending for this service on the astatic needle, although the latter is usually relied on, will abundantly appear hereafter.

The trunk is made hollow, because it has other duties to perform. It is intended to contain one prong of a magnet made exactly in the shape of what musicians call a "tuning fork," except that the prongs are nearer together, being just the distance that the two needles are from each other on their spindle. This magnet slides in and out of the trunk, which it exactly fits; it is so placed, that one prong is always vertical over the other when it is in use.

Its duty is occasionally to assist the directive power of the terrestrial magnetic meridian, and thus to lessen the influence of deflective forces on the needle. With needles of very great sensibility, very weak deflective forces will often produce deflection $= 90°$, and then the galvanometer is incapable of indicating any greater effect. The magnet is graduated in inches and tenths, on both prongs, in order to regulate its proximity to the astatic needle, and therefore its influence in experiments which require repetition or correspondence. The prongs are square, as well as the trunk in which one or the other slides; and one side of the trunk has a spring which presses on the magnet and enables it to slide evenly. Were the prongs cylindrical as well as the trunk, the magnet might turn to one side or the other, and then the other prong would exercise an undue influence on the astatic needle. When the magnet is not required in an experiment, it should be drawn out and put aside at a considerable distance. One prong is marked N, the other S; sometimes one must be uppermost, sometimes the other. It is easy to see how it should be placed in order to moderate the effect of a deflective force on the needle.

It is usual to graduate the circle from 0 to $90°$, on each side of the magnetic meridian line. There is an inconvenience in this mode: in some experiments, the voltaic action, which is the cause of the deflection, exists but for an instant; there is no permanent effect to measure, nor any effect beyond one sudden start of the needle, and its immediate return. Yet sometimes the momentum is such as to carry the needle far beyond $90°$, and even to whirl it round several times. I think it more convenient that the graduation should be carried to $180°$.

The next thing to be considered in the construction of a galvanometer is the compound or so-called astatic needle, a subject of great importance and curious interest. A needle may be defective in two chief points: it may have too little sensibility, by having a strong directive tendency; or it may have too much, by having been brought too near the state of perfect astaticism: in the latter case, a weak deflecting force will produce a maximum deflection, and the needle will be insensible to all higher degrees of energy.

To avoid these imperfections, I employ the following construction, having discarded the common compound needle, which consists of two bars *permanently fixed* to one spindle. The lower bar of the needle is secured, in the usual manner, to the lower end of the spindle; but the upper one is moveable on the

upper end of the spindle, and turns round on it as on an axis: it may be secured in any position by means of a minute nut which screws it against a shoulder on the spindle. Yet the total weight is trifling. One of my compound needles, thus constructed, weighs but $2\frac{1}{4}$ grains, including the nut; its bars are distant from each other $\frac{1}{5}$ of an inch; each is $2\frac{5}{6}$ inches in length, and $\frac{1}{24}$ inch in width; their sides are parallel. The best material for the bars is the mainspring of a small Geneva watch; it is very thin, and retains magnetism a long time. When saturated with magnetism, it no doubt dissipates a portion in a few days; but it retains about one-third for any length of time, and this is sufficient for ordinary purposes. It is obvious that the bars must be filed perfectly straight, and placed parallel to each other.

The following is the process which I employ for magnetizing the compound needle when great sensibility is not required. I caused a horse-shoe magnet of considerable power to be made, the limbs of which, from one extremity of the two polar faces to the other, are of such extent and thickness that the compound needle intended to be magnetized can rest its whole length on the faces. The limbs of the horse-shoe should approach each other within half an inch. In this way the compound needle will rest one edge of each bar on the terminal faces of the magnet, being placed exactly between the two limbs, and in the same situation that its keeper generally occupies. The compound needle will become saturated with magnetism in four hours. Before it is removed, the keeper of the horse-shoe should be put on laterally, close to the extremities, to facilitate the removal.

The needle is now capable of two different applications. If it be intended to measure powerful deflective forces, it is ready for that purpose, so far as its state of magnetism is concerned. But as the two north poles are together, the needle has acquired a dip, and it is necessary to balance this exactly by the counterpoise sliders already mentioned. The needle, when properly placed in the galvanometer, being not astatic, it will give short, quick oscillations, will require no small voltaic energy to deflect it to 90°, and will return to zero with great precision and promptitude. It is now in its least sensible form.

Should greater sensibility be required, we have only to turn the upper bar round on its axis until it be precisely reversed, and to remove the counterpoise towards the centre. To reverse the bars with precision is no easy matter, as will be seen hereafter.

It will be found very convenient thus to have a needle susceptible of a strong directive tendency by causing the poles to act in concert, or of greater sensibility by their acting in opposition; for in this way, and with the occasional aid of the forked magnet, a great range of voltaic forces may be measured. With ordinary galvanometers, if the sensibility be great, a very feeble deflecting force carries the needle to its maximum, and no greater force can be estimated.

When the bars have been reversed, as described above, the instrument will be found to possess the usual sensibility of astatic needles; but not a sufficiency for all purposes, especially when it is intended as a measure of heat. In this case, other proceedings must be resorted to, which, after a few preliminary observations, I will describe.

During some experiments on different modes of communicating magnetism to needles, results were obtained which I am not aware have been observed by others, or made the subject of inquiry. I sometimes produced a compound needle which found its position directly across the magnetic meridian, instead of coinciding with it. As often as it was moved into the right position, it would return to the wrong one; and the more care I took to insure an equally distributed magnetism, the more certainly would this perplexing anomaly recur. It would be useless to trouble the Academy with all the particulars; it will suffice to say that, in order to investigate the cause of these failures, and provide a remedy, I was obliged to contrive a new instrument. As it would be difficult to refer to its employment without giving it a name, I will here call it a volta-magnetometer, the prefix being sufficient to distinguish it from the magnetometer used for a different purpose.

The volta-magnetometer consists of a horizontal brass graduated circle, or ring, fixed directly over and parallel to a circular brass plate of the same total diameter. Their distance from each other, maintained by three stout brass studs, is a quarter of an inch, sufficient to allow free space for the oscillation of the compound needle of the galvanometer, which is to be transferred to it as occasion may require, one bar of the needle lying above the graduated ring, and the other between the latter and the circular brass plate. On the circular brass plate is engraved a circle, corresponding with that of the upper graduated ring: both circles are graduated and numbered with such precision, that each degree on the upper circle is exactly vertical to the corresponding one underneath. The degrees on the lower circle are carried a little farther in towards

the centre than those on the upper circle, to enable the observer to take the two corresponding degrees in his view, along with the interposed points of the needle, when his eye is directed vertically over the four objects, so that they shall all coincide. As a further facility, the numbers are engraved *inside* the circle. The instrument stands on levelling screws, which are received in holes in a brass ring screwed to a wooden stand; and the whole is covered by a French shade. A stop which acts underneath the stand checks tedious oscillations.

From one of the three studs which support the upper circle, proceed horizontally two long brass blades hinged to it in such a manner that they can be made to approach towards or recede from each other. When brought together, they fit closely by their straight edges, and constitute a kind of forceps capable, by its long handles, of firmly grasping the spindle of the compound needle when it is suspended in the centre of the graduated circles. By means of a sliding clip, they can be retained in this position. The silk fibre, which sustains the compound needle, is suspended from a pin in a cross bar at the top of a pillar, in the same manner as in the galvanometer, and is similarly circumstanced in all respects with regard to the adjustments which have been already mentioned. A compound needle, with its silk fibre and pin, may thus be transferred from one instrument to the other, and will fit exactly in either.

Experiments made with the volta-magnetometer soon convinced me that the apparently anomalous position assumed by the needle, which I had taken so much pains to render astatic, and which nevertheless stood perpendicularly to the magnetic meridian, was in strict accordance with the circumstances under which it was placed. To explain the matter, it is necessary to advert to what the properties of a compound needle would be, if, as its name expresses, it were really astatic. If the four poles of the needle, supposed to be perfectly similar in magnetic power, be placed in the same vertical plane, with the synonymous poles contiguous to each other, the directive power will be at its maximum. If in this state of things the bars be opened out, no matter what the angles subtended by them may be, the law of the parallelogram of forces comes into operation: the compound needle will take such a direction, that the resultants of the parallelograms, two sides of which are the intersecting magnetic axes, will bisect the vertical angles which include the magnetic meridian, and will, therefore,

coincide with it. The resultants will represent the intensity of the directive forces of the compound needle, and in reasoning on the subject may be substituted for them. In proportion as the bars of the needle are opened, and the vertical angles which include the magnetic meridian are enlarged in consequence, the resultants or directive forces diminish in energy, until at length the bars are entirely opened and lie with their dissimilar poles contiguous, exactly in the same vertical plane: the resultants then vanish; there is no longer any directive force; and consequently the needle will remain in any position.

This state of indifference depends on the condition laid down, that the four poles possess exactly the same intensity and distribution of magnetism, and that the bars lie precisely in the same vertical plane with the synonymous poles contiguous to each other. If this position of the bars be ever so little disturbed, by turning one of them on the common axis away from the other, even to the amount of one or two degrees, the resultants begin to exert their influence, weakly, it is true, but sufficiently to cause the compound needle, previously indifferent, to take up a position at right angles with the magnetic meridian, because the resultants coincide with it. In that position the needle will permanently remain, and if disturbed, will, after a few oscillations, return to it. Thus the apparently anomalous phenomenon, which surprised me because it had never been previously observed, is very easily understood.

If, instead of equal distribution of magnetism, the power of one bar of the compound needle exceed that of the other, the needle, instead of becoming indifferent when both bars are brought into the same vertical plane, will obey the predominant power of the stronger bar, and pass at once into the magnetic meridian. Indeed the tendency to do so may be exhibited before the two bars are brought into the same vertical plane; the resultants, still feebly in operation, may more or less antagonize the predominant power of the stronger bar; a balance of the two forces will take place; the compound needle will take up a position nearer to or farther from the magnetic meridian, according to the degree of resistance which the resultants offer: but if the bars be brought into the same vertical plane, the resultants will be eventually overpowered.

In order to bring the compound needle to a right angle with the magnetic meridian, the deviation of its bars from the vertical plane must be more or less

according to the greater or less predominance of magnetism in one of them: and the more equal the distribution of magnetism is amongst the four poles, the nearer to the same vertical plane may the bars be brought without causing them to swerve from the right angle at which they stand with the magnetic meridian; although, when they are precisely in the same vertical plane, the needle loses all tendency to that or any other position.

The condition of greatest sensibility is that in which the resultant is barely so far overpowered by the predominant magnetism of one bar, that the needle turns very slowly into the magnetic meridian from being at right angles with it, and in passing through 180° occupies from 30 to 36 seconds.

There is sometimes great difficulty in obtaining the results described: the magnetic axes may not coincide with the metrical axes, so that when the bars appear to be in the same vertical plane, the magnetic axes are not so: the true poles may not be equidistant from the centres of the bars: the magnetism may be irregularly distributed, owing to peculiarities in the steel; and all these circumstances may combine. Empirical trials are, in such cases, the only resources; and patience will insure success.

The volta-magnetometer is capable of imparting sensibility to galvanometer needles in two ways: first, by affording means of distributing the total quantity of magnetism between the four poles in a degree so nearly equal, that the feeblest directive power only will remain, and thus the least resistance will be offered to weak deflecting forces. Secondly, by causing the needle to assume a true position with regard to the magnetic meridian, and thus enabling it to give a *just* estimate of a deflecting force acting on it, which, as we have seen, it does not always present. By means of this instrument, we can prepare needles of any degree of directive power, and can describe that degree in giving an account of experiments. Results obtained by persons at a distance from each other may be compared, when the sensibility of the compound needle made use of is expressed numerically: it may be so expressed by stating the number of degrees by which the magnetism of the two bars of the compound needle differ, when tested on the graduated circles of the volta-magnetometer: this will very nearly give the sensibility, but absolute precision cannot be attained.

I have already described the process of magnetization by which the compound needle acquires sufficient sensibility for ordinary purposes; but if required to

be in its condition of greatest sensibility, we must proceed as follows. It is to be transferred to the volta-magnetometer, and its spindle or common axis is to be confined between the blades of the forceps. The upper bar is to be turned on the common axis until it form any angle with the lower one, suppose 80°: the forceps being opened, the needle will oscillate, and finally settle in such a position, as will show the relative intensity of the poles by the degrees pointed to on the graduated circles. If the magnetism be equal, the four poles will stand at 40°. But it has been already shown, that this equality may be but apparent, owing to the want of coincidence between the magnetic and metrical axes. In order to test this, the bars are to be closed until they fall into the same vertical plane, the poles being reversed. If the compound needle, when liberated, after oscillating a while, turn very slowly into the magnetic meridian, no more need be done; for although some little irregularity in the distribution of the magnetism is thus manifested, the desired effect is obtained. If the needle do not turn into the magnetic meridian, the bars are to be again opened to an angle of 80°, one of the poles is to be touched with the opposite pole of a strongly magnetized steel wire, or sewing needle, until there be a difference of 1° on the indications of the bars. This, or less, will be sufficient difference, when the bars are closed, to carry the compound needle into the magnetic meridian. Should the difference be more than 1°, that bar nearer the magnetic meridian line should be touched with the similar pole of the magnetized wire, and by lessening or increasing its power, the difference of 1° may be attained. The spindle being then caught in the forceps, the upper bar of the needle is to be turned round on the common axis, until the reversed poles appear in the same vertical plane. But a want of precise coincidence in this respect, between the reversed poles of the bars, to an amount often undiscoverable by the eye, will cause the compound needle to lie at right angles with the magnetic meridian. Hence, to produce perfect coincidence, the eye must be assisted by a magnifier, and the compound needle must be executed with great precision so that the bars shall be straight, and identical in all their dimensions. The mode of viewing the needle is of great consequence. The eye must be placed in such a situation that the four objects concerned shall be seen in the same vertical line; namely, the degree on the lower circle, the point of the lower bar, the corresponding degree on the upper circle, and the point of the upper bar. The

needle being adjusted, the spindle is to be disengaged from the forceps. If the reversed poles precisely coincide in the same vertical plane, the needle will oscillate, and finally settle in the magnetic meridian, provided that it retains sufficient directive tendency. If the needle do not lie directly north and south, other trials must be made, and generally the process of perfect adjustment is tedious and troublesome.

It sometimes happens, as already observed, that the magnetism of the bars is equal, and the needle has no directive power. In such a case, the slightest touch of a magnetized wire to any one of the poles of the compound needle will increase or lessen its power, and thus alter the balance: the slighter the alteration the better.

The predominant magnetism should be so feeble, that the needle will very slowly fall into the magnetic meridian; but the predominance should be adequate to produce that effect. If the bars be not precisely in the same vertical plane, they will have a weak tendency to cross the magnetic meridian : but having also a directive power, they will be acted upon by the two forces, and will point at the degree on the graduated circles which expresses the balance of forces. In this state the needle is unfit for service; for although the deflection from the magnetic meridian thus produced may amount to a few degrees only, it will resist a weak tendency to deflection in the opposite direction, when the galvanometer is employed to measure voltaic action, and may modify even a stronger one. Thus the condition of the needle most conducive to sensibility is that of being retained *precisely* in the magnetic meridian, with the feeblest predominance of magnetism in one bar, which is adequate to this effect.

A needle is frequently found to lie in the magnetic meridian, not because its bars coincide with precision in the same vertical plane, for perhaps they do not at the time, but because the magnetism of one or the other bar is so strong as to overpower the great error which would have arisen in consequence. The volta-magnetometer will detect the offending bar, by the inequality of the angles to which the poles will point on the graduated circles when the bars are opened out, and it may be weakened to the necessary degree by the similar pole of the magnetized wire. Needles which point truly north and south, on account of this inordinate predominance of power in one bar, are deficient in sensibility; and when a needle has extreme sensibility, it may be that it points erroneously for want of sufficient predominance.

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In this state of extreme sensibility the needle is subject to making unaccountable excursions, amounting to 5°, 10°, or 12° east or west. On one occasion, when I had suspended a needle by a new silk fibre, it hung for that day exactly north and south. Next morning, at five o'clock, it was found 8°; at nine o'clock it was 0, and so remained all day. These changes recurred every day, about the same hours, during the month of April. On some days, the excursion and return took place twice. About the fifth week, the needle stood constantly at 8° for two days; it then shifted to 10° in the opposite direction, but returned to 0 in the middle of the day. I endeavoured to trace these changes to torsion by an hygrometric quality of the silk, or to alterations of temperature, but could not come to any certain conclusion, although I still attribute them to either or both of these causes, knowing no other that could operate.

Be this as it may, these variations in the direction of the needle would be a source of false estimation of any deflective force, were the galvanometer planted according to the indications of a needle thus in error: and variations will more certainly occur, the greater the sensibility of the needle. The remedy, however, is easy: the pin which sustains the silk fibre may be turned round ever until the needle point accurately; but this mode of rectification is only admissible on the condition that the position of the galvanometer has been rectified by its independent compass needle, and its magnetic meridian line: and here is another use of this needle and line; without them, what errors might in such cases be committed.

I have frequently found, that when the compound needle was adjusted exactly north and south by the volta-magnetometer, it pointed 10° or 12° differently when carried to a different room where the galvanometer was stationed to receive it: hence the rectification of the needle by the volta-magnetometer should be effected beside the galvanometer.

From what has been said, it is evident that the volta-magnetometer is only necessary when needles of exceeding sensibility are required. In ordinary cases, the method of magnetizing already described, or that commonly practised, is sufficient.

Having now brought under notice the erroneous bearing which the compound needle is apt to assume, and the possibility of its being in error, even to the amount of 90°, when the deviation of one bar from the vertical plane of the other is so small as to be undiscoverable by the eye, it is obvious how bad a

guide such a needle is for determining the position of the galvanometer in order to render it fit for use. Yet, as hitherto made, we have no other means of setting the instrument in the magnetic meridian than to turn it round on its axis until the compound needle point north and south on the graduated circle. It is true that so great an error will only be possible when the needle is brought unusually near the astatic state; but it will be considerable in proportion to the sensibility attained. The magnetic meridian line and compass needle, which I have added to the galvanometer, afford a protection against this source of fallacy.

One immediate ill consequence of the error of the needle, should it exist undiscovered and uncorrected, is, that it affects those degrees of the circle which are of most value in delicate galvanometry. The first twenty degrees are in the direct ratio of the deflecting force, which no other degrees on the circle are. The effect of terrestrial magnetism is as the sine of the angle comprised between the magnetic meridian and the magnetic axis of the needle on which it acts. The sine of 20° is as nearly as possible double the sine of 10°; but beyond 20° the virtual ratio cannot be determined without submitting each particular galvanometer to an experimental investigation. And more than this, if the experimenter shall have taken the trouble of ascertaining the value of the degrees above the twentieth, by MELLONI's, or any other method, it will prove unavailing; for the whole scale of ratios of deflecting forces to angular deflections becomes deceptive if the magnetic meridian line of the galvanometer do not correspond with the terrestrial magnetic meridian. When the instrument is used as a galvanoscope, a small error is perhaps of little consequence, except that it causes the needle to represent deflecting forces weaker or stronger than they really are; but when it is used as a measure of heat, and for some other nice purposes, a want of coincidence between the magnetic meridian of the instrument and the terrestrial magnetic meridian would be productive of serious error. It is therefore evident how useful is the addition of the magnetic meridian line, with its point and compass needle, for setting the galvanometer due north and south: it at once detects the error of the astatic needle, if such exist.

On the subject of the coil, it may be proper to mention that, although it is often made of copper wire covered with cotton, such a covering is altogether unfit. I have observed that one of my galvanometers, which is furnished

with a cotton-covered coil, although sometimes as sensible as most others, often becomes singularly otherwise. On such occasions, it will not be affected by a thermo-electric current generated by the heat of the fingers on two wires, bismuth and antimony, soldered together, which at another time would move the same needle 60° or 80°. I have not been able to connect these failures with any particular states of the weather, although such states may be the cause, acting perhaps on the hygrometric properties of the cotton. Coils covered with silk are not subject to this uncertainty in their action.

As silver is said to be the best of all conductors of electricity, it might be supposed that the wire of the coil should be of that metal. I made comparative trials of silver and copper coils, each resembling the other in every respect except the metal. I could perceive no decided difference in their effects, but imagined the copper to have some little advantage, and therefore adopted it. The difficulty of covering *pure* silver wire with silk is, as I am informed, great; and this, along with the cost of the silver, made a difference in the total cost of the galvanometer of more than £3. The advantage, if there be any, is certainly not commensurate.

I conceive that, in the generality of galvanometers, the coil and its frame are too narrow: there is certainly an advantage in having them so broad that they extend on each side nearly to the whole diameter of the graduated circle which covers them.

To conclude:—the improvements in the construction of galvanometers, here suggested, may be summed up as follow:—1. The addition of means, independent of the astatic needle (which may greatly err), for setting the instrument in the magnetic meridian. 2. The close approximation of the needles to the coil. 3. The removal of obstructions to the rotation of the needle. 4. The means of inducing in the bars of the needle the least difference of polarity that is consistent with their function. 5. A method of detecting and preventing derangement of the needle arising from forces which cause in it a tendency to stand transversely to its true position. 6. A construction of the needle which renders available the operation of a strong or a weak directive force, as may be required. 7. The introduction of a controlling graduated magnetic power for increasing or diminishing the deflecting influence of voltaic forces on the needles.

I venture to hope that these improvements, along with the several adjustments and facilities added, will render the instrument more convenient, will increase its sensibility, and contribute to the accuracy of its indications.

Some persons may conceive that the sensibility, to attain which I have taken so much trouble, is practically redundant. I can only say that I have experienced the absolute necessity of the arrangement described, during my late investigation of the laws of tribothermo-electricity, some of which would have remained unknown but for the excellence of the galvanometer made use of. I need not again refer to the delicacy required for thermometrical experiments.

NOTE.

I EXTRACT from the Proceedings of the Academy the following observations on this communication, made by the Rev. Dr. LLOYD, President:

" The President observed, that all the facts respecting the position of equilibrium of the astatic needle, to which Mr. DONOVAN had directed the attention of the Academy, and which (as far as he was aware) he has been the first to notice, were immediate consequences of theoretical laws.

" When two magnetic needles are united by a fixed vertical axis passing through their centres, and perpendicular to both, the moment of the force exerted by the earth upon them is the sum of the moments which it exerts upon each needle separately, and is, therefore,

$$X \, (M \sin u + M' \sin u');$$

in which M and M' denote the *magnetic moments* of the two needles, u and u' the angles which their *magnetic axes* make with the magnetic meridian, and X the horizontal component of the earth's magnetic force. In the state of equilibrium this moment is nothing; so that if u_0 and u_0' denote the corresponding values of u and u', there is

$$M \sin u_0 + M' \sin u_0' = 0. \tag{1}$$

Consequently, if two lines be taken from any point of the vertical axis, parallel to the magnetic axes of the two needles, and proportional to their magnetic moments, M and M', the diagonal of the parallelogram constructed upon them must lie in the magnetic meridian, when the compound needle is at rest.

" Again, if we substitute $u = u_0 + v$, $u' = u_0' + v$, in the general expression of the statical moment, it becomes, in virtue of (1),

$$X \, (M \cos u_0 + M' \cos u_0') \sin v$$

Hence the compound needle is acted upon as a single needle, whose *magnetic axis* lies in the direction of the diagonal of the parallelogram above mentioned, and whose *magnetic moment* is

$$\mu = M \cos u_0 + M' \cos u_0'. \tag{2}$$

Accordingly, the diagonal of the parallelogram already referred to will represent in magnitude the magnetic moment of the compound needle. For, if the equations (1) and (2) be squared, and added together, and the angle contained by the magnetic axes of the two needles, $u_0' - u_0$, be denoted by a, we have

$$\mu^2 = M^2 + 2MM' \cos a + M'^2. \tag{3}$$

" In the case of the *astatic* needle, $a = 180 - \delta$, δ being a very small angle, and $\cos a = - \cos \delta = - 1 + \frac{1}{2}\delta^2$, *q.p.* whence

$$\mu^2 = (M - M')^2 + MM'\delta^2. \tag{4}$$

Accordingly, whem $M - M'$ is not a very small quantity, the second term may be neglected in comparison with the first, and $\mu = M - M'$, nearly. On the other hand, when $M - M' = 0$, we have $\mu = M\delta$.

" Returning to (1), and substituting for u_0' its value, $u_0 + a$, we have

$$\tan u_0 = \frac{- \sin a}{\dfrac{M}{M'} + \cos a} \; ; \tag{5}$$

by which the position of the needle with respect to the magnetic meridian, when at rest, is determined. In the case of the astatic needle the preceding equation becomes

$$\tan u_0 = \frac{- M'}{M - M'} . \delta \sin 1'. \tag{6}$$

From this we learn,

" 1. That the tangent of the angle of deviation of the astatic needle from the magnetic meridian varies, *cæteris paribus*, as the angle δ, contained by the magnetic axes of the two component needles.

" 2. That, however small that angle be, provided it be of finite magnitude, the tangent of the deviation may be rendered as great as we please, and therefore the deviation be made to approach to 90° as nearly as we please, by diminishing the difference of the moments of the two needles."